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# AN ACOUSTIC IMPACT METHOD TO DETECT HOLLOW HEART OF POTATO TUBER

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## ABSTRACT

*An acoustical sorting system was developed to detect hollow heart of potato tubers (Spunta variety). The system includes a microphone, digital signal processing hardware and material handling equipment. It was found that upon impact with a steel plate, potato tubers with no hollow heart emit sound with higher signal magnitudes than with hollow one. Linear discriminate analysis was used to classify potato tubers using three features extracted from the microphone signal. One of the discriminate features is the integrated absolute value of microphone output signal. The other two features are the number of data points in the digitized microphone signal after impact that have a slope and signal magnitude below preset threshold levels. The classification accuracy of this system is approximately 98%. The internal quality of potato tubers can be detected by acoustic impact method. The resonant frequency of potato tubers after dropping was found from acquired signal. The hollow heart existence of potato tubers can be evaluated by the resonant frequency of vibration signal of dropping tubers. This technology of acoustics to evaluate the hollow heart existence is more reliable and accurate especially for export.*

## INTRODUCTION

Egypt produces 1.8 ~ 2.0 million tons of potato every year and Spunta variety is one of the most used tubers by consumers (Ag. Res. Center Bulletin, 2005). The hollow heart in potato tubers actually due to the exceesd of nitrogen fertilizer during growing specially for bigger tubers such as Spunta variety. Both hollow and black heart are not seen by human eyes.

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Some researches have been done on watermelon quality, pistachio nut shell and egg shell using acoustic impact methods but there is no research on hollow heart of potato tubers.

Brown center and hollow heart are physiological disorders of the potato tuber and arise at a higher incidence when growing conditions abruptly change during the season. This can arise when the potato plants recover too quickly after a period of environmental or nutritional stress. When the tubers begin to grow rapidly, the tuber pith can die and/or pull apart leaving a void in the center (Hochmuth, et al 2001). Hollow heart is characterized by a star shape hollow in the center of the tuber ( Fig. 1) on the other hand, brown center frequently precedes the development of hollow heart. Hollow heart and brown center negatively impact tuber quality. Disorders make the tubers unattractive and can reduce repeat sales but severe hollow heart negatively impacts the quality of chip processing potatoes. However, both disorders are reported as not harmful and do not affect the taste or nutrition of the tuber. USDA has established grade and quality standards and recommendation for potatoes to help potato growers and shippers market their product in wholesale channels.

Fig. (1): Characterized hollow heart by a star shape hollow in the center of the tuber.

Texture is one of the most important quality factors of fruits and vegetables. Most acoustical food evaluation systems have been developed to detect firmness in fruits. Sonic and vibration response method is one technique for predicting the textural quality of agricultural products nondestructively. Armstrong et al. (1990) mentioned that flesh firmness is used as an indicator of apple texture or maturity. Technique, as suggested by USDA (1978), for firmness determination include Magness-Taylor firmness testing, thumb pressure, wax development, cutting and chewing test. Yamamoto et al. (1980) compared Magness-Taylor firmness with apple resonant frequencies when excited by this method. Several researchers have found an inverse correlation between fruit firmness and resonant frequency (Duprat et al., 1997 and Stone et al., 1998). Most of the acoustical systems developed was tapping the food with a plunger, recording the resulting sound, then digitally processing the microphone signal to extract dominant frequency bands or other signal features correlated with firmness. Younce and Davis (1995) developed such a system to measure firmness of cherries using impact acoustics. Sugiyama et al. (1998) developed an acoustical firmness tester for melons that measured sound transmission velocity. This technique eliminated some error caused by size and shape variations in the fruits.

Most farmers can not predict the internal quality of potato tubers at all. From this viewpoint, Takeda et al. (1970) made an instrument for nondestructive evaluation of apple ripeness by measuring sound when the product was hit by impact. The technology of analyzing the sound was to find a relationship between natural frequency and maturity of the product. Clark (1975) also used the same idea to predict the ripeness of watermelons. Chyung, (1997) investigate the internal qualities of watermelon, such as maturity, cavity existence and orientation, using acoustics by impulse striking. The watermelon was struck by a hammer and the produced sound was acquired by a directional microphone and signal analyzer to find out the relationship between peak frequency and quality. Several different acoustic methods to evaluate food quality have been investigated. McCambridge et al. (1996) developed an acoustic method to detect freeze cracking in different food during freezing. This study found that when cracks occur they produce sounds of higher amplitude and frequency than background noise. Pearson (2001) developed an acoustical sorting system to separate pistachio nuts with closed shells from those with open shells. He concluded that, the improved sorting accuracy of nuts allows 4.6% more open-shell product to be classified as open shell. On the other hand, Cetin et al (2004) developed an algorithm using speech recognition technology to distinguish pistachio nuts with closed shells from those with open shells. They observed that upon impact, nuts with closed shells emit different sounds than nuts with open shells and the classification accuracy was more than 99% on the validation set.

The objective of this work was to investigate the feasibility of using impact sound as a means to detect hollow heart of Spunta potato tubers for high quality export product.

## MATERIALS AND METHODS

Potato tubers (Spunta variety) were collected from the local market at three different locations according to their size and common use. Three hundred tubers were chosen depend on their outer appearances (100 tubers from each location). The potatoes used in this study were stored in the cold storage at a temperature of 12 °C and 85 percent relative humidity. They were taken out of cold storage 24 hours before testing and permitted to reach room temperature. The room temperature was recorded before starting the experiment and found to be 22-25 °C. Potatoes were brought randomly to the room temperature (22-25 °C) 24 hours before testing. Each potato was numbered, weighed, and its tuber length and diameter was measured. All tubers were tested daily, by the nondestructive experimental setup, to determine resonant frequencies and other acoustic parameters.

### System design

The system was designed to drop potato tubers to an impact surface, acquire the sound signal upon impact, process the data, and then divert the product into either with hollow heart or without hollow heart (Fig. 2). The roller conveyer was constructed of polished stainless steel ( 3.0 mm thickness) to form a trough declining to an impact container. The bottom of the container covered with a 2.0 mm thickness of a sponge cushion to reduce potato bruising during impact. The impact container was made of 30 x 30 mm polished stainless steel bar. The large thickness was required to minimize vibration of the bar when impacted by a potato tubers. A highly directional microphone (MS45 and K9 powering module, Osaka Electronics Corporation) was used to minimize the effect of ambient noise and the external noise effect was controlled by amplifier. Output of the microphone was connected to a digital signal processor (DSP) card hosted in a personal computer (Pentium 3 processor, 164 MHz, Windows 2000 operating system). This DSP performed the analog-to-digital conversions at 5000 kHz. When a potato tubers impacted the container, the microphone output signal ranged from 0 to 1.0 V. Data acquisition began when the microphone output rose above 0.05 V. This threshold level was sufficient to trigger acquisition on virtually all tubers, while preventing false triggering from ambient sound. Data acquisition continued for 2.0 ms after triggering producing 360 features (data points).

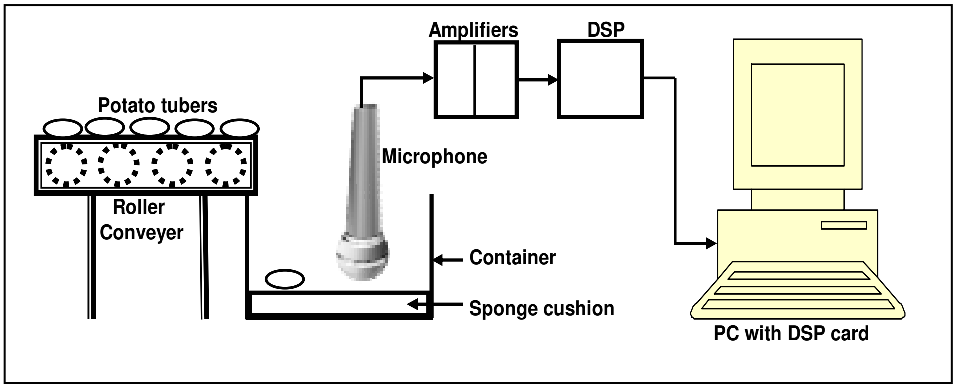

Fig.( 2): Schematic diagram of the experimental and impact sound sorting system.

### Signal processing and resonant frequency measurement

Data points (features) used were limited to those that could be computed in real time with a sorting rate of one tuber/s. Sorting at this rate required a minimal lag time (5 seconds) between obtaining the data to make a decision and taking the dropped tuber out of the container. Thus, Features were extracted from either the absolute value of the signal level (signal magnitude), the absolute value of the signal gradient, or both. Signal gradient was computed from the following equation:

$$\mathbf{G}_{x} = |\mathbf{I}_{(x - gap)} - \mathbf{I}_{(x + gap)}| \qquad (1)$$

where $\mathbf{G_x}$ is the signal gradient value at data point **x**, $\mathbf{I_x}$ is the signal level value at location x and gap is the interval between data points.

The tuber was placed on a damping cushion and only direct sound waves produced by dropping without reflection. The directional microphone was hanging in the container in order to enable the microphone to measure directly the sound of the dropped tubers. The directional microphone was connected to a signal analyzer (B&K 1800 Dual Channel). The acquired signal, on the time and frequency (Fast Fourier Transform, FFT) domain, were shown on the signal analyzer panel and saved into disk. Potato tubers were divided into the categories of hollow inside and no hollow inside. The hollow in the tuber directly influence the resonant frequencies and the acoustic response was acquired by a directional microphone. First of all the consistency of the signal was confirmed. When the tuber was dropped with different forces, the main peak frequency on tuber surface remains at same position.

## Hollow existence measurement

To find the hollow, some marks were made on each tuber around the equator and cross section lines. The marks were divided into 4 parts by each $90^{o}$ along circumference of the tuber. The tuber was dropped on each mark (twice on the hip side and twice on the sharp side) and placed the microphone on the opposite side of it by taking the tuber out of the container and dropped it again so the main peak frequency was obtained. After dropping the tuber four times and record its data, the tuber was cut into two half to see by human eye that the tuber has a hollow or not. This way make us sure about the existence of hollow heart or not and compare human eye results with the experimental data. Each mark separated 90 angular degree on each tuber circumference. When a tuber was dropped at some specified marks, the main peak splits up in two or three different peaks. Each response was collected every $90^{o}$ of rotation about its long axis. A total of 360 data points (features) were computed for each tuber. However, a maximum of four of these data points could be computed in real time with the installed DSP hardware. Using all possible combinations of two, three, and four data points, a program "C" was written to exhaustively search for the best subset of features for classifying tubers as with or without hollow. Both linear and non-linear discriminate analyses were used as the classification procedure (Huberty, 1994). The discriminate functions were trained on odd numbered samples and tested, or validated, on even numbered samples. The feature set achieving the lowest error rate on the validation set was recorded and programmed into the DSP hardware for real time feature extraction and sorting.

### Damping ratio

The internal damping of structures is an important parameter in modal analysis (Braun, 1986; Inman, 1989). The task is to measure the natural frequencies, the damping ratios, and the amplitudes associated with each resonant peak of the frequency response. Damping in fruit may be associated with fruit maturity, degree of ripeness and composition of fruit tissue. Two algorithms were examined during this study to assess the internal damping of tubers. The first algorithm is the conventional adaptation of damping ratio of a second-order vibrating system, for a more complex structure. If the damping is low and the natural frequencies are well apart from each other, every mode-shape corresponding to a resonant frequency may be approximated by a second-order system of a single degree of the freedom model. The frequency response of this model can be calculated as follows (Galili, et al 1998):

$$\mathbf{H = K \ / \ [\ (1\text{-}w'^{2})^{2} + 4D^{2} w'^{2}\ ]^{1/2}} \qquad (2)$$

where **H** is the signal amplitude at a frequency **w**, **w'** is the frequency ratio $\mathbf{w/w_n}$ , **K** is a parameter related to the input amplitude and the internal damping and $\mathbf{w_n}$ is the resonant frequency of the model.

The conventional method used to identify the damping ratio of this model is the half-power technique, where two half-power resonant frequencies ($\mathbf{w_1}$ and $\mathbf{w_2}$) are identified for each resonant peak. The damping parameter **D** is then calculated by the expression:

$$\mathbf{D = (w_2 - w_1) / (2w_n)} \qquad (3)$$

By using only data points close to $\mathbf{w_n}$ the effect of the non-uniform input, caused by the mechanical impulse in this frequency range, may be reduced. An additional frequency-related parameter, the centeroid of the frequency response, was attempted in this study. This last acoustic-response parameter is very simple for on-line calculation. In addition, it does not depend on a specific resonant frequency, but on the entire spectrum of the frequency response, a feature that could be important when testing asymmetric tuber that introduces several close resonant frequencies.

## RESULTS AND DISCUSSION

### Hollow existence

Table 1 shows some typical data of main peak frequencies for some potato tubers of three different location in Egypt. The multivariate discriminate analysis procedure in SAS (1990) was utilized to find the detection criteria among the three locations. The analysis showed that no big different among peak frequencies of the three locations and the main peak frequencies kept almost at a constant level. On the other hand, there was a different of peak frequencies between tubers with hollow heart and tubers without hollow heart. For example at location 1, the average peak frequencies was 1.157 kHz, location 2 was 1.142 kHz and location 3 was 1.123 kHz for the tubers without hollow heart. The average peak frequencies of the tubers with hollow heart were 0.957 kHz, 0.942 kHz and 0.918 kHz for locations 1, 2 and 3 respectively. The analysis also indicated that, average peak frequency different between hollow tubers and no hollow ones were 230 Hz, 210 Hz and 210 Hz for location 1, 2 and 3 respectively with SEP (Standard Error of Prediction) of 0.019.

From experimental data analysis, it was found that, peak frequency of hollow tubers is lower than that of no hollow. There is a range of about 201Hz to distinguish from hollow existence. Classification accuracy of the acoustic method was greatly improved by increasing the number of training sounds. Only four out of 300 tubers were misclassified in all cases which represent more than 98% of accuracy. It is however possible to detect the hollow existence using acoustic technology.

**Table (1) : Some main peak frequencies of detecting hollow heart tubers at three different locations.**

| Tubers without hollow heart | | | Tubers with hollow heart | | |
|---|---|---|---|---|---|
| **L. No. 1** | **L. No. 2** | **L. No. 3** | **L. No. 1** | **L. No. 2** | **L. No. 3** |
| **Freq. (kHz)** | **Freq. (kHz)** | **Freq. (kHz)** | **Freq. (kHz)** | **Freq. (kHz)** | **Freq. (kHz)** |
| 1.21 | 1.15 | 1.11 | 0.98 | 0.94 | 0.91 |
| 1.15 | 1.14 | 1.12 | 0.96 | 0.94 | 0.91 |
| 1.17 | 1.14 | 1.11 | 0.98 | 0.95 | 0.92 |
| 1.18 | 1.15 | 1.11 | 0.95 | 0.94 | 0.92 |
| 1.16 | 1.16 | 1.12 | 0.96 | 0.94 | 0.92 |
| 1.16 | 1.17 | 1.13 | 0.94 | 0.95 | 0.92 |
| 1.15 | 1.17 | 1.13 | 0.97 | 0.95 | 0.92 |
| 1.14 | 1.15 | 1.14 | 0.95 | 0.95 | 0.93 |
| 1.16 | 1.16 | 1.11 | 0.96 | 0.94 | 0.93 |
| 1.12 | 1.16 | 1.12 | 0.94 | 0.96 | 0.92 |
| 1.20 | 1.14 | 1.12 | 0.93 | 0.95 | 0.92 |
| 1.14 | 1.09 | 1.13 | 0.94 | 0.94 | 0.93 |
| 1.15 | 1.11 | 1.15 | 0.95 | 0.94 | 0.92 |
| 1.14 | 1.12 | 1.15 | 0.94 | 0.93 | 0.91 |
| 1.16 | 1.13 | 1.12 | 0.96 | 0.93 | 0.91 |
| 1.15 | 1.14 | 1.11 | 0.98 | 0.93 | 0.91 |
| 1.15 | 1.14 | 1.12 | 0.94 | 0.94 | 0.92 |
| 1.14 | 1.14 | 1.13 | 0.94 | 0.95 | 0.91 |
| 1.15 | 1.15 | 1.12 | 0.95 | 0.94 | 0.93 |
| 1.14 | 1.14 | 1.12 | 0.97 | 0.94 | 0.91 |
| 1.14 | 1.14 | 1.12 | 0.97 | 0.93 | 0.92 |
| 1.17 | 1.13 | 1.12 | 0.98 | 0.93 | 0.91 |
| 1.17 | 1.14 | 1.13 | 0.97 | 0.94 | 0.92 |
| 1.18 | 1.14 | 1.12 | 0.95 | 0.95 | 0.93 |
| 1.16 | 1.14 | 1.11 | 0.96 | 0.95 | 0.92 |
| 1.15 | 1.14 | 1.12 | 0.97 | 0.94 | 0.90 |
| 1.16 | 1.15 | 1.12 | 0.96 | 0.94 | 0.91 |

**Notes:** L. No. 1: (Location 1 of Dakahleia Governorate), L. No. 2: (Location 2 of Gharbeia Governorate) and L. No. 3: (Location 3 of Kafr Elsheikh Governorate).

The potato tuber was placed in the container after impact and the acoustic tests were repeated four times. Digitized impact sound signals from each tuber were stored for off-line analysis as shown in figure 3. Using discriminate analysis, it was desired to extract a limited number of features from the digitized microphone signal to accurately classify tubers as either with or without hollow heart. The correlation between the resonant frequencies detected in the positions was very high (R=0.97) and a lower correlation was found between the damping ratio (R=0.65). No conclusion has been found yet about the preferred tuber position in this case.

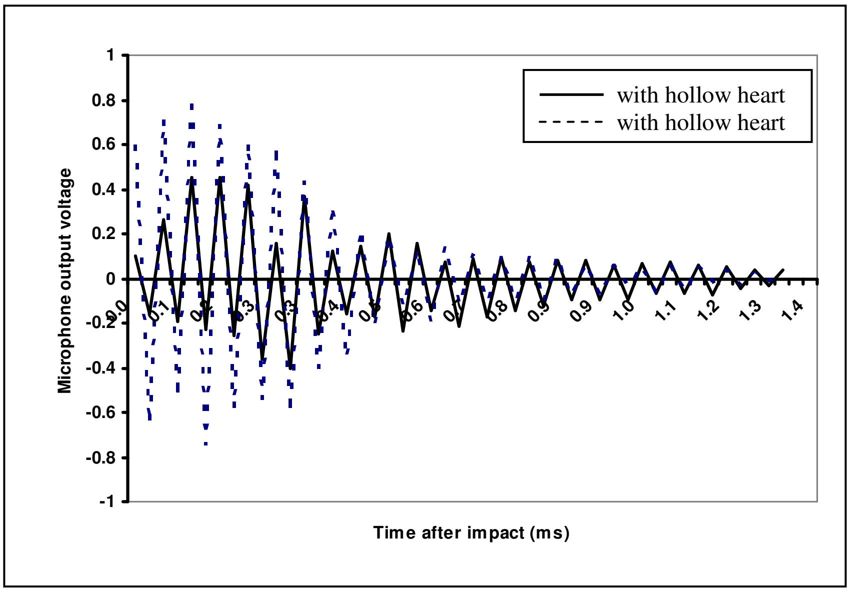

Figure (3): Digitized microphone signal of Spunta potato tuber with and without hollow heart

Figure (4) shows the normalized spectral amplitude obtained from the impact sound of Spunta potato tubers (with or without hollow). For this plot, frequency spectra for individual tuber was computed using a Hanning window (Brigham, 1988) on the first 256 data points sampled after impact then, the spectra was averaged. The frequency of sounds emanating from potato tubers (with or without hollow) was slightly different. Hollow heart tubers exhibited a peak near 3000 Hz, while undamaged tuber (without hollow) have high normalized amplitude. As shown, a one standard-deviation error bar on each of these spectra overlap. Thus, the extracted features used to distinguish potato tubers split types relied heavily on the signal magnitude or a combination of the signal magnitude and gradient.

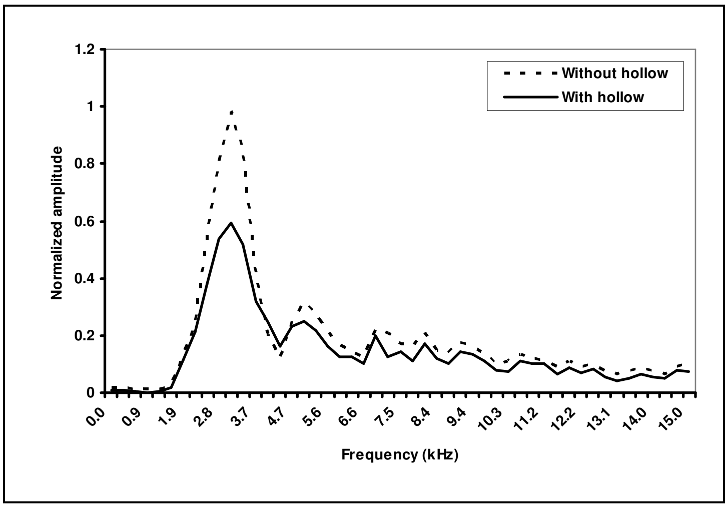

Fig.( 4): Average frequency spectra magnitudes of the impact sound of Spunta potato tuber with and without hollow heart

## Variation of acoustic signal with tuber position

To have a visible signal, an offset of 0.2 relative amplitude units were added and two resonant frequencies of different amplitude could be detected depending on the tuber location (Fig. 5).

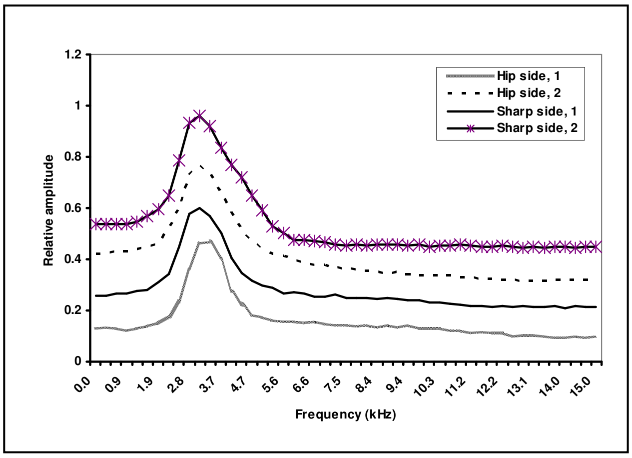

Fig. (5): Effect of tuber position on the acoustic signal and resonant peaks.

However, the same first resonance was clearly defined in all tests by the search algorithm (Equations 2 and 3). It was concluded that consistent readings can be achieved within a limited range of tuber position, despite its irregular shape. The accuracy and repeatability of the piezoelectric measurement system was tested with the 300 tubers. The axis symmetrical tubers were dropped in the container and tested simultaneously by three sensors. Consistent frequency response was obtained when repeated tests were conducted at the same location on the tuber, this consistency was evident even with irregular acoustic signals. Small variations of the natural frequencies, in steps of 11.9 Hz, could be detected while the tuber was successively rotated relative to its axis of symmetry. It was concluded that the acoustic test is repeatable and that accuracy of 11.9 Hz can be obtained when measuring the natural frequencies of a tuber.

**Damping Parameters**

The calculation of the damping ratio is demonstrated in figure 6. Two complex tuber response curves observed for resonant frequencies (not shown) are well apart from each other and the curve-fitting (Fig. 6) procedure according to the half-power method (Equations 2 and 3) could be applied. The new algorithm for calculation of the damping ratio which uses data points close to the peak, could be applied in this case as well. The limitations of the half-power method when the signal has two close natural frequencies are obvious and fitted curve of a single degree of freedom is quite far from the original data.

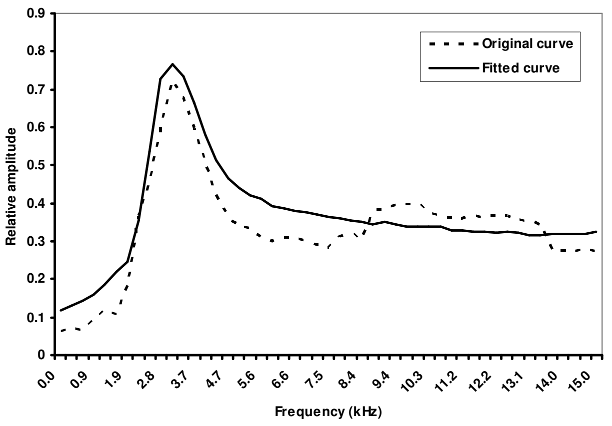

Fig.(6): Single degree of freedom curve fitting and damping ratio determination.

The same signal was analyzed by the new algorithm for the damping ratio as demonstrated in figure 6. The data points used for the calculation are marked in the figure. The fitted curve, which should represent the first mode-shape, is very close to the data points in this range of spectrum.

**Area of power spectrum**

Figure 7 shows the relationship between the average area under the power spectrum for the all data sets of 300 Spunta potato tubers and the difference between maximum and minimum area. The maximum and minimum area differences for the normal tubers (no hollow) were mostly higher than those of with hollow tubers. This was due to the higher magnitude in power spectrum of the normal tubers than that of with hollow tubers as shown before in figures 3 and 4.

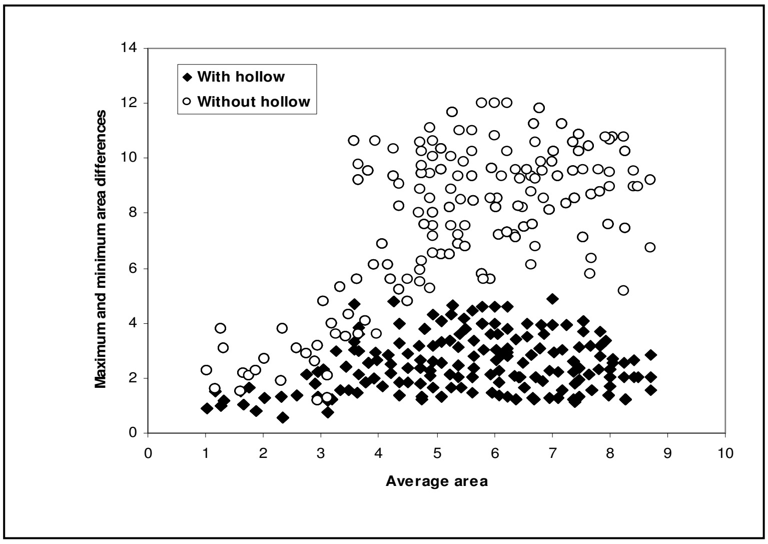

Fig.(7): Average area and difference between maximum and minimum area in normalized power spectrum curve for hollow and no hollow tubers.

The differences in maximum and minimum areas for normal tubers were higher than those of with hollow tubers because the four sound responses (two hip sides and two sharp sides) from a normal tubers were more uniform than those of with hollow tubers. The criteria to distinguish hollow tubers could be drawn from the average area or differences between maximum and minimum areas or both of them.

## CONCLUSION

The hollow heart existence and orientation of potato tubers can be evaluated by resonant frequencies of acoustic signal through an impulse vibration. This study showed the feasibility of distinguish the tubers with hollow heart and without hollow heart by impact acoustics. The criteria to distinguish hollow tubers could be drawn from the average area or differences between maximum and minimum areas or both of them. The correlation between the resonant frequencies detected in the positions was very high (R=0.97) and a lower correlation was found between the damping ratio (R=0.65). Only four out of 300 tubers were misclassified in all cases which represent more than 98% of accuracy.

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## الملخص العربى

# استخدام طريقة الصدمة السمعية لفحص القلب الاجوف لدرنات البطاطس

ابراهيم السيد البطاوى*    محمد سيد عمران**

وجود القلب الأجوف فى درنات البطاطس ،والذي لا يمكن رؤيته من الخارج، يقلل من سعرها كمحصول ويقلل من ثقة المستورد في الصادرات المصرية لذلك كان الهدف من هذا البحث تكوين آلية بسيطة ودقيقة لفحص القلب الأجوف في درنات البطاطس يمكن إدخالها في نهاية خط الفرز والتدريج وتستخدم هذه الآلية طريقة الصدمة السمعية والتي تعتمد بصفة أساسية على تخزين الترددات الرنانة الناتجة من الصوت ثم تحليلها لمعرفة مدى وقيمة هذه الإشارات وذلك حسب قوة الصوت الناتج. ولإجراء هذه التجارب تم استخدام درنات البطاطس (صنف سبونتا) وعمل آلية لنقل الدرنات ( كبديل لسيور التدريج أو الفرز ) تتكون من سير مبطط يتحرك على اسطوانات دوارة وذلك لنقل الدرنات من مكان الاستقبال لتسقط بالتتابع على قاع صندوق معدني لاستقبال الدرنات عند إسقاطها ، سمك قاع الصندوق3 مم ومبطن بطبقة سمكها 2مم من الإسفنج وذلك لتقليل احتمالية حدوث كدمات للدرنات نتيجة سقوطها على سطح صلب، ميكروفون لاستقبال الصوت الناتج عن تصادم الدرنات مع قاع الصندوق، ومكبر ومنقى للصوت (Amplifier)– ونظام (Hard wear ) لتخزين و وتحليل الإشارة الصوتية الناتجة من درنة البطاطس بعد إسقاطها في الصندوق المعدني.

وباستخدام طريقة التحليل الخطى المتميز (Linear Discriminate Analysis ) يتم تكامل ودمج قيم الإشارات المطلقة الخارجة من الميكروفون عند حدوث صوت نتيجة تصادم الدرنة مع قاع الصندوق ، ثم تخزين وتحليل أرقام الإشارات الصوتية الناتجة بعد عملية إسقاط الدرنات.

ومن نتائج التجارب تبين أن درنات البطاطس ذات القلب الأجوف تحدث صوتا ذو ترددات أقل من البطاطس السليمة، وعليه فانه باستخدام هذه الآلية يمكن بالنظر المجرد اكتشاف الدرنات ذات القلب الأجوف عن طريق التردد الرنيني للإشارات الصوتية الناتجة بسبب التصادم وذلك بدقة وصلت إلى 98% ويتم فصلها يدويا، ويمكن في دراسات تالية ابتكار آلية لفصل هذه الدرنات آليا.

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